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SUBJECT: SEMI-ANNUAL PROGRESS REPORT FOR THE PERIOD DECEMBER 31, 1969 TO JULY 1, 1970. THE WORK ACCOMPLISHED DURING THIS PERIOD WILL BE REPORTED UNDER THE FOLLOWING HEADINGS:

Task 1. Performance Investigation

Task 2. Heat Transfer Investigation

Task 3. Combustion Stability Investigation

I. Introduction

Progress during the last report period has been made in the following areas:

A. The analysis of the performance data has been completed and the results indicate that the accuracy was effected adversly by two factors; first, the short duration of the experiments precluded the possibility of obtaining reliable steady state thurst and secondly, the use of ablative nozzles made the determination of an accurate throat area difficult.

B. Heat Transfer. The analysis of throat ablation rate data was completed. No conclusive correlations were obtained which related run time, mixture ratio, chamber pressure, injector configuration, pulsing, and nozzle run number with linear ablation rate. The writeup of the data was started.

Work began on the new phase of the heat transfer study, the primary objective of which is to measure heat fluxes using a water-cooled copper tube mounted on the engine axis line. The chamber pressure and mixture ratio to be used were determined analytically. Work on hardware is presently under way.

C. The report period saw the completion of the combustion instability experiments on the large and small tube, 7 element quadlet injectors and initiation of construction of the single element quadlet configuration.

II. Status of Work in Progress

A. Task 1 Performance

A detailed analysis of the data obtained for use in the evaluation of performance has indicated basically two factors which affect seriously the accuracy of the resulting values obtained in this phase of the program. These factors are the short duration of the experiments dictated by the hardware configuration and the use of ablatives in the throat which made the determination of an instantaneous throat area difficult.

Although the oscillograph traces of the load cell output appeared to have reached steady state it was noted that thrust coefficients were quite low. Examination of calcomp plots of load cell output developed from previous analyses indicated that the starting transient appeared to be a heavily damped second order system response and that steady state was not achieved. An attempt was made to determine the equation for this system and predict from it the final steady state value. A regression analysis was attempted to obtain a functional form of the dynamic response for the load cell thrust stand system, but proved unsuccessful. It was noted however that the averaging of points through the transient resulted in a curve very closely approximating the response of a first order system and an approximate time constant was obtained. When the function value was sixty-three per cent of the final value, the time corresponded to twenty-eight data points, or one data record. This number of data points corresponds to a time of two and one-half milliseconds. Considering the response of a first order system, it is generally accepted that the response is ninety-nine per cent of the final value after five time constants. For many of the runs of this analysis, shut-down occurs prior to a time interval corresponding to five time constants.

As the load cell has the longest response time, if compensation for this response lag could be employed, this time lag could be eliminated. The approximate dynamic response relationship obtained was

$$\frac{\theta_o}{\theta_i} = A(1 - e^{-t/2.5})$$

As the normalized thrust is used, the constant A is equal to one.

The application of this correction, it is felt, does not provide a sufficiently accurate correction, therefore further investigation is being given the second order system model which should result in an improvement but still within the limitations of method. Additional run duration on the single element injector should improve the accuracy of the thrust correction factor on the previous data.

It was planned to acquire additional performance data on the combustion stability experiments, however the EECO digital data system was inoperative. Repair expertise was not available at the Jet Propulsion Center and EECO no longer builds a system, only the components. In view of the foregoing, EECO was not receptive to repair or maintenance and that coupled with the system familiarization required of our technicians caused an extended down time for this system. Last month EECO finally consented to assist in the trouble shooting and the system was again put into service the last month of this report period.

B. Task 2. Heat Transfer

1. Ablation

The development of a method to measure heat transfer by instrumenting the ablative chamber liner and nozzle of the high pressure rocket engine was terminated to permit initiation of a revised program described later in this report. The lack of sufficiently accurate thermophysical data for the ablative material made it virtually impossible to estimate the accuracy of heat fluxes calculated from the ablation data that was to have been taken. The mathematical model, proposed to calculate heat fluxes, introduced considerable error due to the approximation required to employ it. With the pressure of an early initiation of the revised program the decision was made to conclude the ablation study with a wrapup report of the linear ablation rates measured at the nozzle throat and a correlation of parametric effects. These data are presented in Figure 1 of this report and will be presented in more detail in a Contractors report being prepared. The run durations given are actual run durations taken from oscillograph traces of chamber pressure versus time. For this study run duration was defined as the time difference on the oscillograph trace between the time where the chamber pressure reached one-half of its steady state run value during the pressure rise at the beginning of a run and the time where the pressure drop at shut down decreased to one-half of the steady state run value. Chamber pressure was measured with a Photocon pressure transducer. Mixture ratio was calculated from propellant flow rate data obtained with Potter turbine meters. The column labeled "Injector" refers to the injector tube sizes for the seven quadlet injector configuration (Figure 2). A value of one in this column indicates that the larger tube sizes were utilized for that respective run and a value of two indicates the use of the smaller injector tube sizes. The "Pulse" column denotes whether or not the pulse gun was fired during a run. A value of two in this column indicates that the engine was pulsed. The column with the "Nozzle Firing Number" arises because of the fact that most of the ablative nozzle inserts have been used for several firings. The number in this column indicates the number of firings that the nozzle insert was used including the listed run. Linear ablation rate at the nozzle throat was calculated by dividing the difference between postfire and prefire throat radius by the run duration. The throat radius was measured with a micrometer at several circumferential locations, the average value of the measurements then being used in the ablation rate calculations.

Three different approaches were taken in analyzing the data. The first was to inspect the data, looking for the effect on ablation rate of varying each parameter of interest (i.e. run duration, chamber pressure, mixture ratio, injector tube size, pulsing, and nozzle run number). Runs were first classed according to whether or not they had the same nozzle run number, injector, and pulsing numbers, which yielded fourteen sets of runs of which five sets were eliminated because they contained only one run. The data of the remaining nine sets were contradictory, percluding the drawing of any conclusions as to the effect of mixture ratio, chamber pressure, and/or run duration. This method was employed using various combinations of parameters and in all cases yielded no obvious trends.

The second approach was to form systems of linear equations from the run data and solve the resulting matrix, of the form [A][X] = [B], for the X's. This was done by first selecting the parameters, whose effect it was desired to study. Then, in order to form a square matrix, a number of runs equal to the number of parameters under study were chosen, data from one run forming one equation. Only the parameters of interest were retained from the run data. Each of these was then multiplied by an unknown constant, the products were summed, and the sum was equated to the ablation rate. The number of parameters studies was varied from a minimum of three to a maximum of six and the combinations of parameters were also changed. A computer program was written to set up and solve the matrix equations. The run numbers used in a given case were randomly selected from the thirty-six runs in the data. Two hundred cases were run for each set of parameters. Results were inconclusive. The constants in the solution vectors not only varied greatly in magnitude from case to case but also changed signs, for all numbers and combinations of parameters.

The third approach to ablation data study was to input the data in a canned statistical data correlation program (reference 1). Output obtained from this program listed correlations between all parameters and the ablation rate of less than .5.

The results of these studies thus far indicate that no firm conclusions can be reached from the analysis thus far as to the effect on ablation rate of the parameters studied. Examination will continue.

2. Copper Tube Study

The primary effort in the heat transfer part of the high pressure rocket engine program has been shifted from the study of ablation to the measurement of heating rates received by a water cooled copper tube mounted on the axis line within the engine (Figure 2). The objectives of this research include looking at high pressure cycling with simultaneous high thermal cycling effects on copper as well as the measurement of heat fluxes.

The first step in this study is to prove the feasibility of the method. This will be accomplished by mounting a single 3/8" O.D., 030" wall, oxygen free half hard copper tube in the engine (Figure 3) and firing the engine. These initial exploratory firings with a single tube will also be used to establish the system parameters (fuel, oxidizer, and coolant run tank pressures) needed for operation at the desired chamber pressure, mixture ratio, and coolant flow rate. During these runs, the only measurement associated with the coolant will be flow rate, as the coolant will be dumped directly into the engine exhaust, thus percluding coolant temperature measurements. Later on in the program, an annular tube arrangement allowing coolant recovery for temperature measurements is planned.

A heat flux of at least 75 Btu/in^2 sec to the tube is desired. In order to determine the chamber and mixture ratio necessary to obtain this value of heat flux, two ICRPG computer programs were used. A one-dimensional equilibrium program (reference 2) was used to determine gas properties in the chamber and nozzle for various chamber pressures and mixture ratios. These data were then input to a boundary layer analysis program (reference 3) using different combinations of run conditions until a combination was found which yielded a sufficiently high heat flux at as low a chamber pressure as possible. The run conditions chosen were 3000 psia chamber pressure and a mixture ratio of 2.0, which give a heat flux, according to the computer results, of 76 Btu/in^2 sec in the chamber which increases to a maximum of 115 Btu/in^2 sec near the nozzle throat.

Work on the modification of the hardware and the test stand was begun during this work period. A hydraulically actuated valve has been located near the engine (Figure 4) and will be used for water flow control. A Potter turbine meter for measuring water flow rates was installed in the feed line between the water run tank and the valve. The previously constructed regimish face cooled injector (Figure 4) is being modified to allow insertion of the copper tube through the center of the injector face. Ablative nozzle inserts to be utilized for firings with the tube have throat diameters of 1.36 inches and were constructed previously.

C. Task 3. Combustion Stability Investigation

A total of eight pulsed firings of the rocket engine, Runs 46-53, were made during this period. For the first three runs, Runs 46-48, the large tube-seven quadlet injector was used. Runs 46 and 48 were successful pulsed runs. The respective run conditions are shown on the Pulsed Run Summary Sheet - Large Tube-Seven Quadlet Injector, and the photocon traces are shown in Figures 6 and 8. On Run 47, the pulse gun power supply functioned properly, but the electrical explosive initiator did not detonate. It was later found that the internal electrical wiring of the explosive initiator was discontinuous. Although Run 47 did not furnish combustion stability data, it was very useful in proving that no electrical interference exists between the electrical pulse initiator and the photocon pressure transducer. Figure 7 shows the pulse gun electrical power supply pulse and shows that there is no electrical interference picked up by the photocon pressure transducer or its circuit. Thus the photocon pressure transducer gives a true measurement of the high frequency response of the chamber pressure during and following the pulse.

With the completion of Run 48, the experimental test program using the large tube-seven quadlet injector was concluded after a total of twelve pulsed runs. Run conditions for the entire series of eight successful runs using this injector are shown on the Pulsed Run Summary Sheet - Large Tube-Seven Quadlet Injector. For this series, mixture ratio ranged from 1.42 to 2.99, with ample data to effectively cover this range. All of these runs were made at a chamber pressure within 5% of the desired 4000 psi. The photocon pressure transducer traces show that for all cases the peak-to-peak pressure pulse was greater than the steady state chamber pressure, which should have been adequate to induce combustion instability. However, in all cases the oscillation damped within 0.005 second. A considerable amount of chemical augmentation of the pulse was experienced during every pulse of the series of runs using the large tube-seven quadlet injector. The degree of chemical augmentation, and its causes and effects are still being analyzed.

The evolution of the pulse gun design continued throughout this period, reaching what appears to be a final design after Run 48. The present pulse gun cross-section is shown in Figure 5. Use of the fiber pulse gun sheath greatly decreased the amount of time and energy expended in extracting the gun from the housing following each run. Whereas the stainless steel pulse gun sheath upset and wedged inside the housing when the pulse was initiated, the fiber sheath breaks into large pieces. These pieces do not enter the combustion chamber, but remain in the pulse gun housing and are removed after the run. Slight upsetting of the heavy stainless steel pulse gun housing with each pulse continues to be a problem. It is believed that the housing will have to be replaced at regular intervals if this continues.

For the latter five runs, Runs 49-53, the small tube-seven quadlet injector was used. Four of these runs produced combustion stability data. On Run 49 the analog tape recorder shut off at the start of the run, due to a malfunction. Therefore, no pulse data were recorded, even though the oscillograph run record shows that the pulse gun fired properly. The respective run conditions for the remaining four of these runs are shown on the Pulsed Run Summary Sheet - Small Tube-Seven Quadlet Injector and the photocon pressure traces are shown in Figures 9 to 12. The experimental test program using the small tube-seven quadlet injector was concluded with Run 53. Run conditions for this series of five runs are shown on the Pulsed Run Summary Sheet - Small Tube-Seven Quadlet Injector. Mixture ratios ranged from 1.525 to 2.15, with ample data to cover this range.

In general the peak-to-peak pressure pulses were much smaller for this series using the small tube-seven quadlet injector than had been recorded in the previous series of runs using the large tube-seven quadlet injector. In fact Figures 10 and 12 show that on Runs 50 and 53, the amplitude of the induced oscillations was very small. These runs were made at the lower mixture ratios of this series (MR = 1.525 and 1.71 respectively). The large difference in peak-to-peak pressure pulses between the large and small tube seven quadlet injectors may be due to the difference in propellant droplet sizes produced by the injector. With the smaller droplets produced by the small tube-seven quadlet injector reacting more quickly, the combustion process had probably reached a greater degree of completeness by the time the propellants had traveled a given axial distance. Thus by the time the propellant-combustion product mixture reached the axial location of the pulse gun, there was less chemical energy remaining which would augment the pulse. Therefore all of the runs using the small tube-seven quadlet injector showed greater combustion stability than did those for which the large tube-seven quadlet injector was used.

All of the data from these two series of runs is undergoing analysis. Several attempts have been made to develop a computer program to fit a curve through the data points which make up the high frequency photocon pressure traces which were recorded during each pulse. So far, the greatest degree of fitting has been achieved using the Periodic Regression and Harmonic Analysis computer program run on the CDC-6500 digital computer. This routine has successfully matched both the harmonic photocon pressure transducer trace characteristic of low frequency combustion instability (chugging) and the damped harmonic curve produced by constructing a curve through the midpoints of the high frequency oscillations following the pulse. These results are shown in Figures 13 and 14. The photocon pressure transducer trace is being analyzed from the standpoint of the theory of superposition of solutions in which the actual pressure trace is to be matched by superpositioning four curves. These four curves are respectively: (1) a step function offset from the chamber pressure before the pulse, which corresponds with the degree of chemical augmentation of the pulse, (2) a steady state harmonic oscillation characteristic of the low frequency combustion instability (chugging) induced by the pulse, (3) an exponential decay of the low frequency oscillations, and (4) the high frequency oscillations overlaid on the curve resulting from the superposition of the first three curves. As mentioned earlier, the computer program has successfully matched both (2) and the curve resulting from the superposition of curves (1), (2), and (3). Some work is still being done toward improving the matching of absolute value and slope of the fitted curve with those of the actual pressure transducer trace at both the start of the pulse and the end of oscillations, where the pressure reverts to the steady state chambers pressure.

III. Plans for Future Research

Performance:

Preparation of the final contractors report on this area will continue and be completed with the conclusion of the single element injector testing.

Heat Transfer:

1. The wrapup report of throat ablation rate data will be completed.
2. Work on hardware for the new phase of the program will be completed and the ensuing initial firings will be made with the single cooled copper tube system as described above.

Combustion Stability:

Fabrication of the large tube-single quadlet continues. As soon as the fabrication and installation of this injector is completed, it will be run at three mixture ratios (MR = 1.8, 2.0, and 2.2). The combustion stability data will be correlated with that obtained using the seven quadlet injectors. Unlike the seven quadlet injectors which had solid faces, the single quadlet injector will employ a face made of Rigimesh which will be cooled by flowing up to 25% of the N_2O_4 through it.

Analysis of the combustion stability data and comparison with existing analytical combustion stability models will continue. The Crocco-Reardon sensitive time lag theory (Ref. 4) will be studied in more detail and analyzed for its applicability to this program. Only the tangential mode oscillations will be studied, since the experimental data were all generated using a tangentially initiated instability. It is planned to develop the analytical sensitive combustion time lag and proper combustion chamber frequencies and compare the predicted stability conditions with the experimental results. Since in all cases, the experimentally induced combustion instability damped very rapidly, a great deal of time will be spent in analytically modeling the damping effects present in the combustion chamber.

PULSED RUN SUMMARY SHEET - LARGE TUBE-SEVEN QUADLET INJECTOR

Run Number	35	41	43	44	45	46	47	48
Average Nozzle Throat Diameter - Inches	1.007	0.917	1.013	1.125	0.973	1.042	0.975	1.012
Chamber Pressure - Psi	3910	3800	4060	4100	4100	4120	4080	4070
Mixture Ratio	1.88	2.67	2.99	2.25	2.10	1.42	1.725	1.89
Run Duration - Sec.	0.90	0.75	0.75	0.85	0.85	0.85	0.75	0.75
Steady State Run Duration Prior to Pulse - Sec.	0.160	0.100	0.100	0.140	0.140	0.200	0.080	0.100
Peak-to-Peak Pressure Pulse - Psi	6080	5270	8550	4820	9180	6240	-	5200
Time to Damp Completely Sec.	0.003	0.003	0.003	0.005	0.004	0.002	-	0.004
Trace Figure Number	Shown in Previous Progress Report					6	7	8

The above runs were made at the following constant conditions:

Chamber length 8.45 inches (L* = 50)

Chamber internal diameter 2.34 inches

RDX Explosive Charge 56.4 grains (10 wafers)

Injector Tube Size - Large Tube-Seven Quadlet Injector

Oxidizer orifice diameter = 0.118 inch

Fuel orifice diameter = 0.106 inch

PULSED RUN SUMMARY SHEET - SMALL TUBE-SEVEN QUADLET INJECTOR

Run Number	49	50	51	52	53
Average Nozzle Throat Diameter - Inches	0.996	1.045	0.982	0.984	1.0672
Chamber Pressure - Psi	3800	3900	4120	4000	4130
Mixture Ratio	2.15	1.525	1.935	2.13	1.71
Run Duration - Sec.	0.75	0.75	0.75	0.75	0.75
Steady State Run Duration Prior to Pulse - Sec	0.110	0.190	0.220	0.160	0.130
Peak-to-Peak Pressure Pulse - Psi	-	1000	3375	2500	2750
Time to Damp Completely - Sec	-	0.002	0.002	0.002	0.002
Trace Figure Number	9	10	11	12	13

The above runs were made at the following constant conditions:

Chamber length 8.45 inches (L* = 50)

Chamber internal diameter 2.34 inches

RDX Explosive Charge 56.4 grains (10 wafers)

Injector Tube Size - Small Tube-Seven Quadlet Injector

Oxidizer orifice diameter = 0.094 inch

Fuel orifice diameter = 0.075 inch

NOZZLE THROAT ABLATION RATE DATA

RUN NUMBER	RUN DURATION (SEC)	CHAMBER PRESSURE (PSIA)	MIXTURE RATIO	INJECTOR	PULSE	NOZZLE RUN NUMBER	ABLATION RATE (IN/SEC)
8	.758	3855	1.42	1	1	2	.0231
9	.752	3955	2.58	1	1	3	.0452
10	.765	4015	1.87	1	1	4	.0720
11	.808	3915	2.42	1	1	1	.0309
12	.600	3995	2.58	1	1	1	.0615
13	.532	3915	1.26	1	1	2	.0705
14	.520	4045	1.54	1	1	3	.0212
15	.630	4005	2.20	1	1	1	.0389
16	.650	4025	2.07	1	1	2	.0845
18	.758	3725	1.81	2	1	1	.1200
19	.790	3995	1.98	2	1	1	.0690
20	.950	3865	2.00	2	1	2	.0426
21	.750	4040	1.50	2	1	1	.0505
22	.795	3765	1.70	2	1	2	.0755

FIGURE I. ABLATION DATA.

23	.740	3965	2.27	2	1	1	.0459
24	.730	3945	1.94	2	1	2	.0790
26	.745	3850	1.74	2	1	3	.0282
27	.652	3800	2.00	2	1	4	.0253
28	.578	3868	2.31	2	2	1	.0615
29	.674	3927	2.14	2	1	2	.0600
30	.721	3801	1.89	2	1	3	.0650
31	.724	3913	2.26	2	1	1	.0456
32	.660	4067	1.08	2	2	2	.0348
35	.833	3910	1.88	2	2	2	.0530
36	.790	4090	1.45	1	2	1	.0386
37	.782	4060	1.76	1	1	2	.0775
38	.786	4020	1.84	1	1	1	.0580
41	.520	3800	2.67	1	2	1	.0540
43	.370	4060	2.99	1	2	3	.0850
44	.430	4100	2.25	1	2	4	.1850
45	.440	4100	2.10	1	2	1	.0535
46	.640	4120	1.42	1	2	2	.0703

FIGURE I, CONTINUED.

47	.390	4080	1.73	1	1	1	.0705
48	.410	4070	1.89	1	2	2	.0817
49	.385	3800	2.15	2	2	1	.0675
50	.520	3900	1.53	2	2	2	.0904

INJECTOR: 1 REPRESENTS LARGE TUBE INJECTOR WITH .118" I.D. OXIDIZER TUBES AND .106" I.D. FUEL TUBES.

2 REPRESENTS SMALL TUBE INJECTOR WITH .094" I.D. OXIDIZER TUBES AND .075" I.D. FUEL TUBES.

FIGURE 1, CONTINUED.

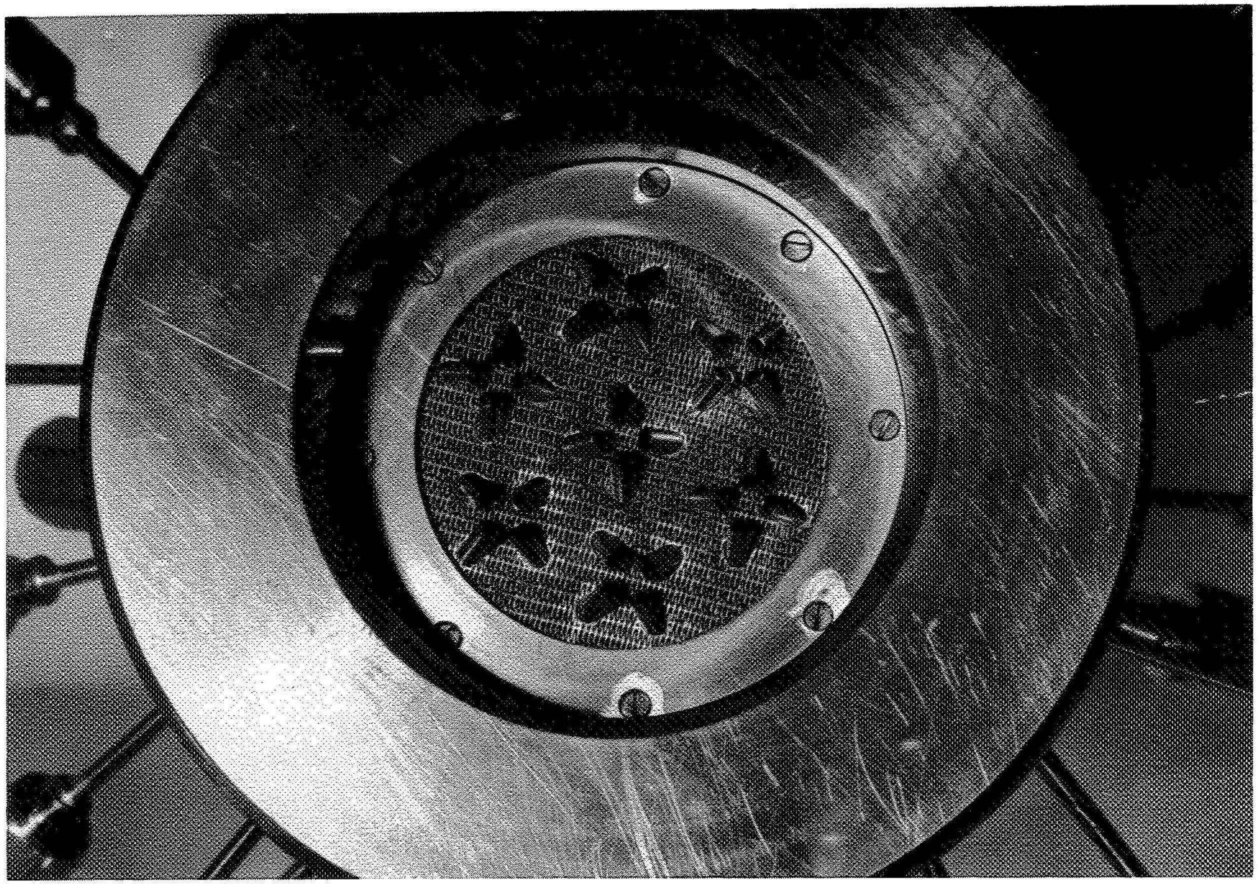


FIGURE 2. RIGIMESH INJECTOR.

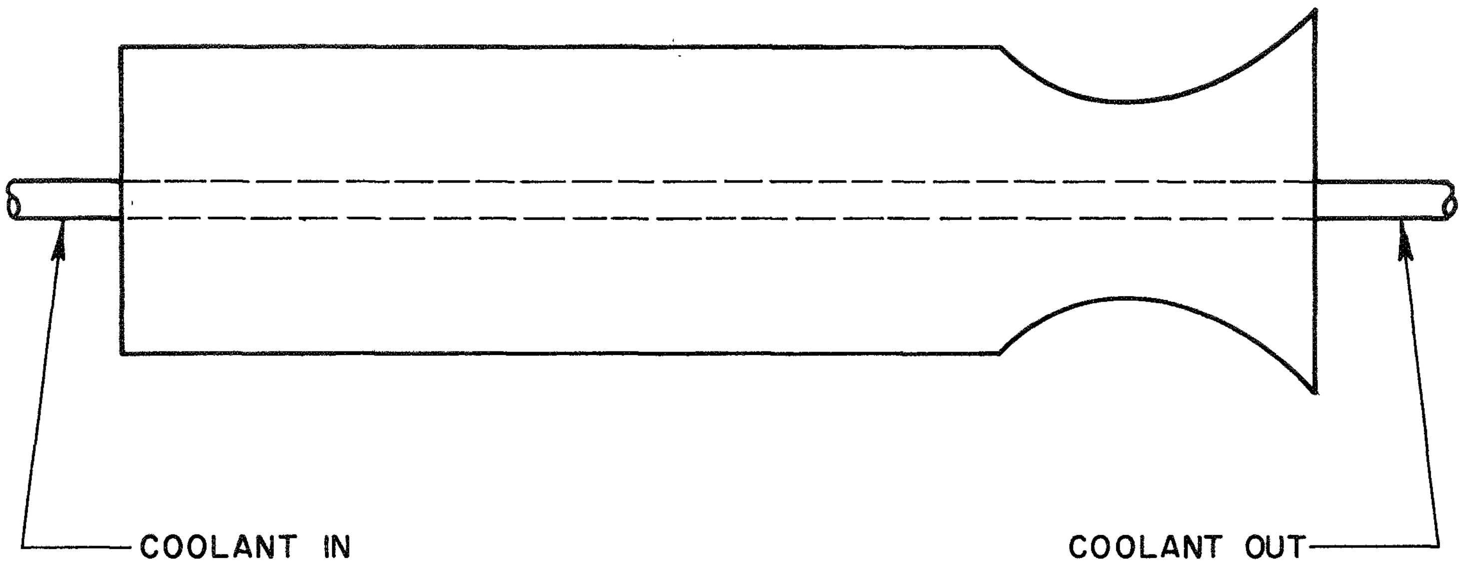


FIGURE 3. SKETCH OF SINGLE 3/8" O.D. TUBE INSIDE ENGINE.

COOLANT VALVE

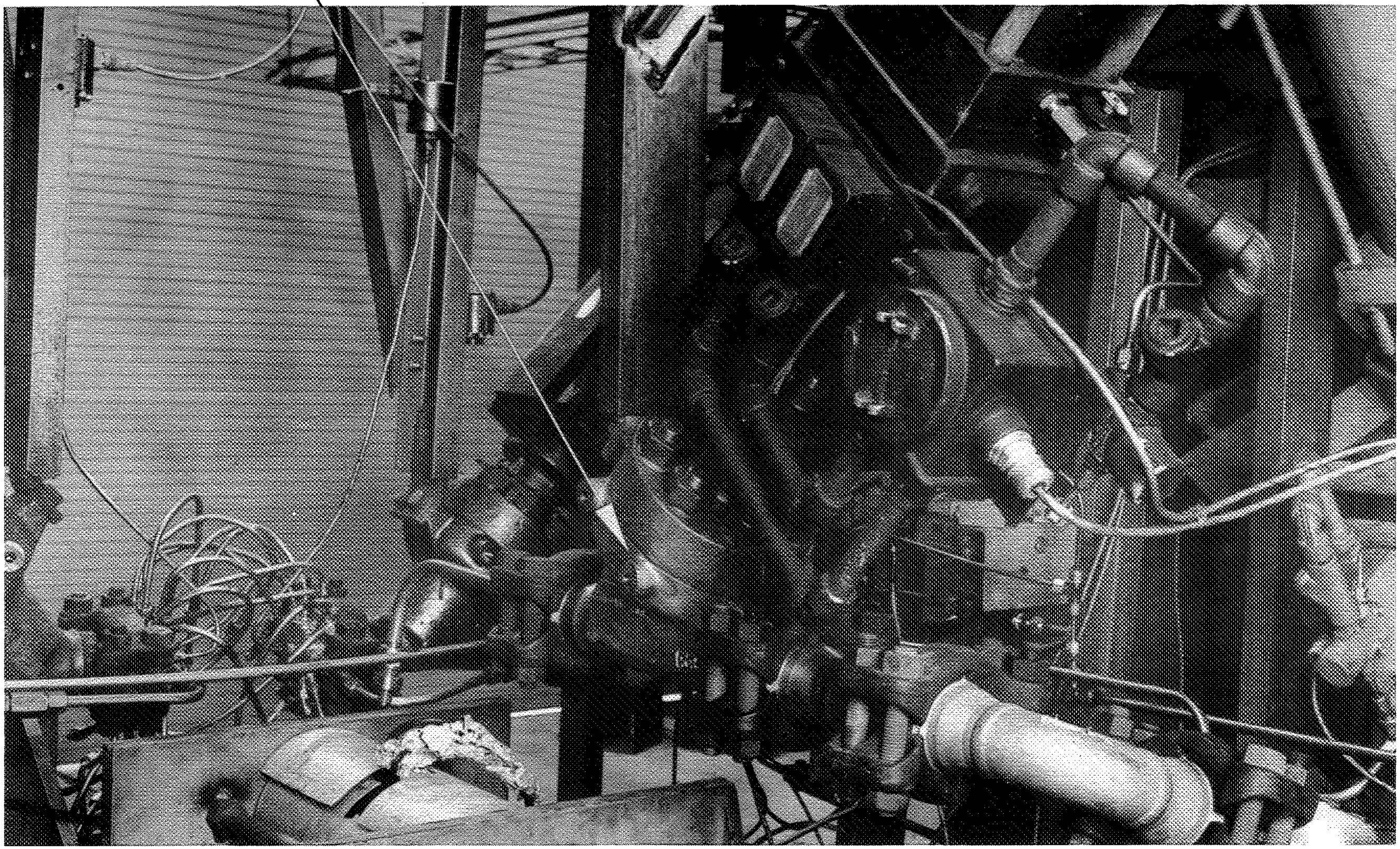


FIGURE 4. COOLANT VALVE.

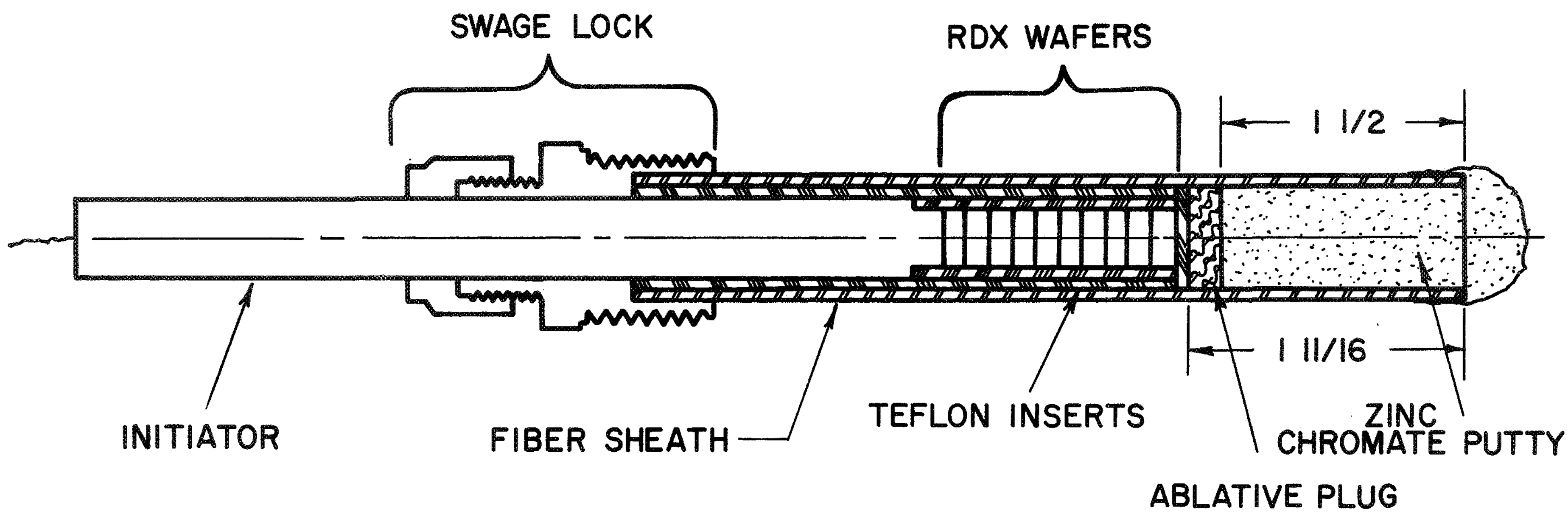


FIGURE 5 PULSE GUN CROSS-SECTION

FIGURE 6 RUN 46 PHOTOCON PULSE TRACE

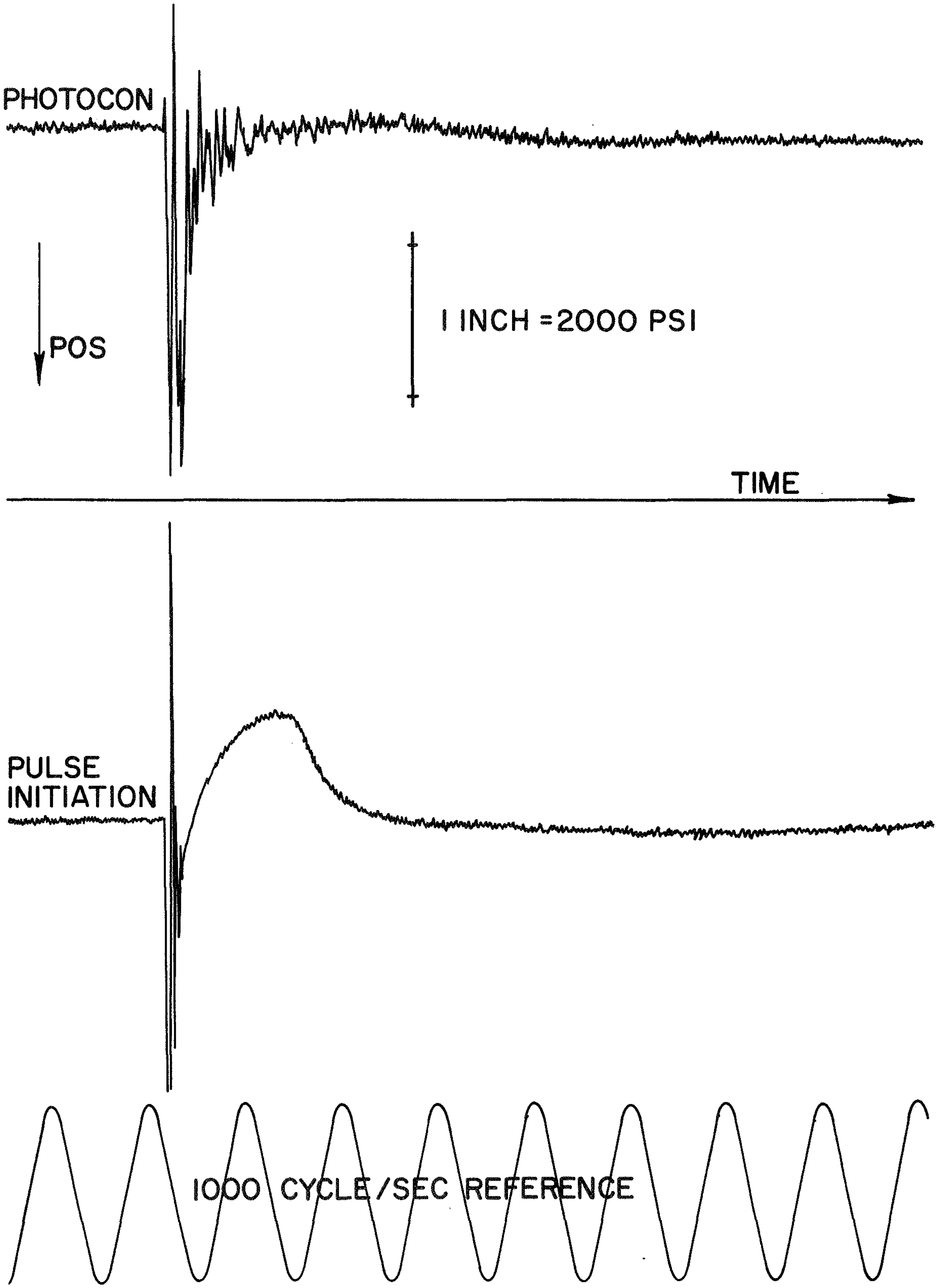


FIGURE 7 RUN 47 PHOTOCON PULSE TRACE

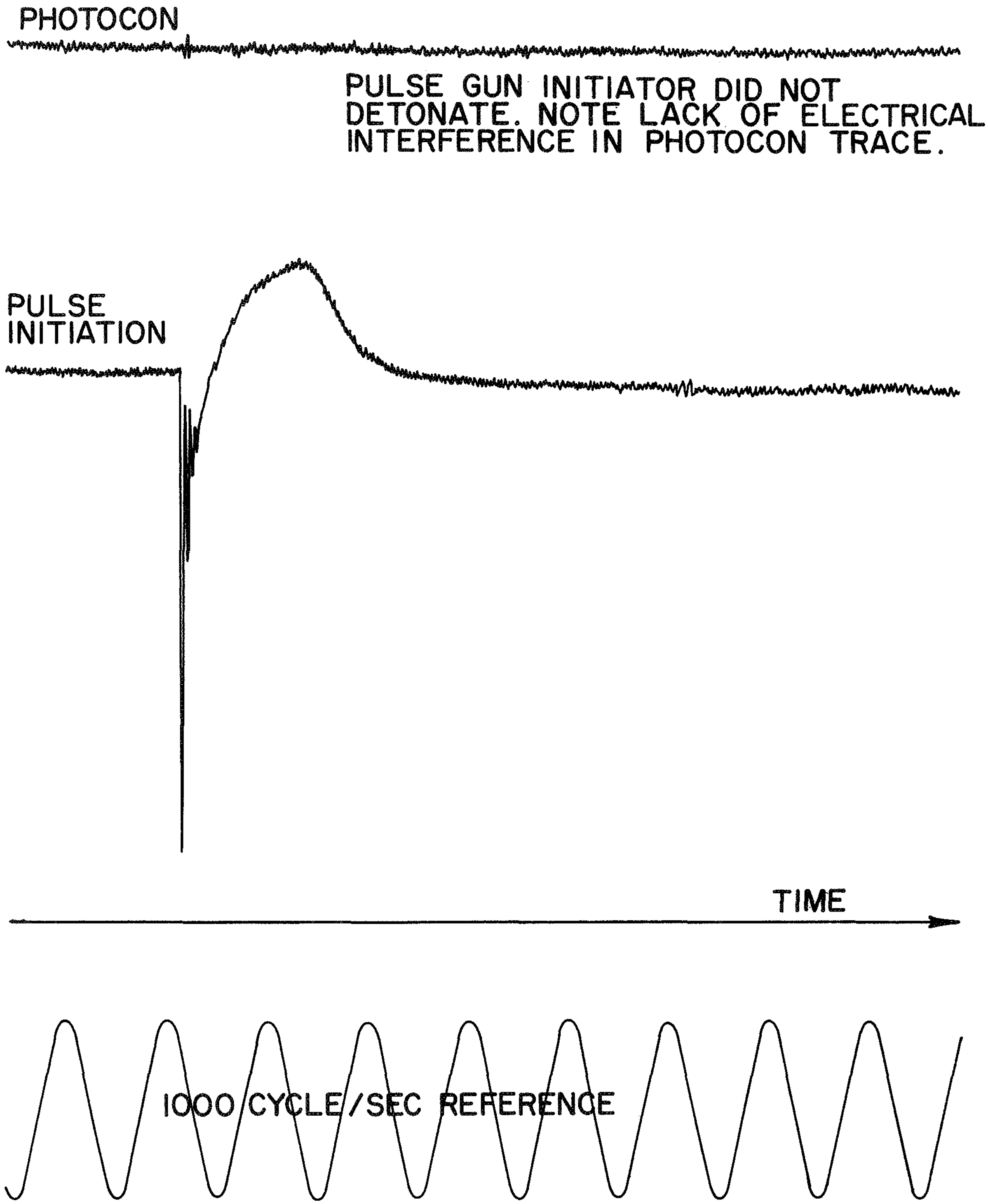


FIGURE 8 RUN 48 PHOTOCON PULSE TRACE

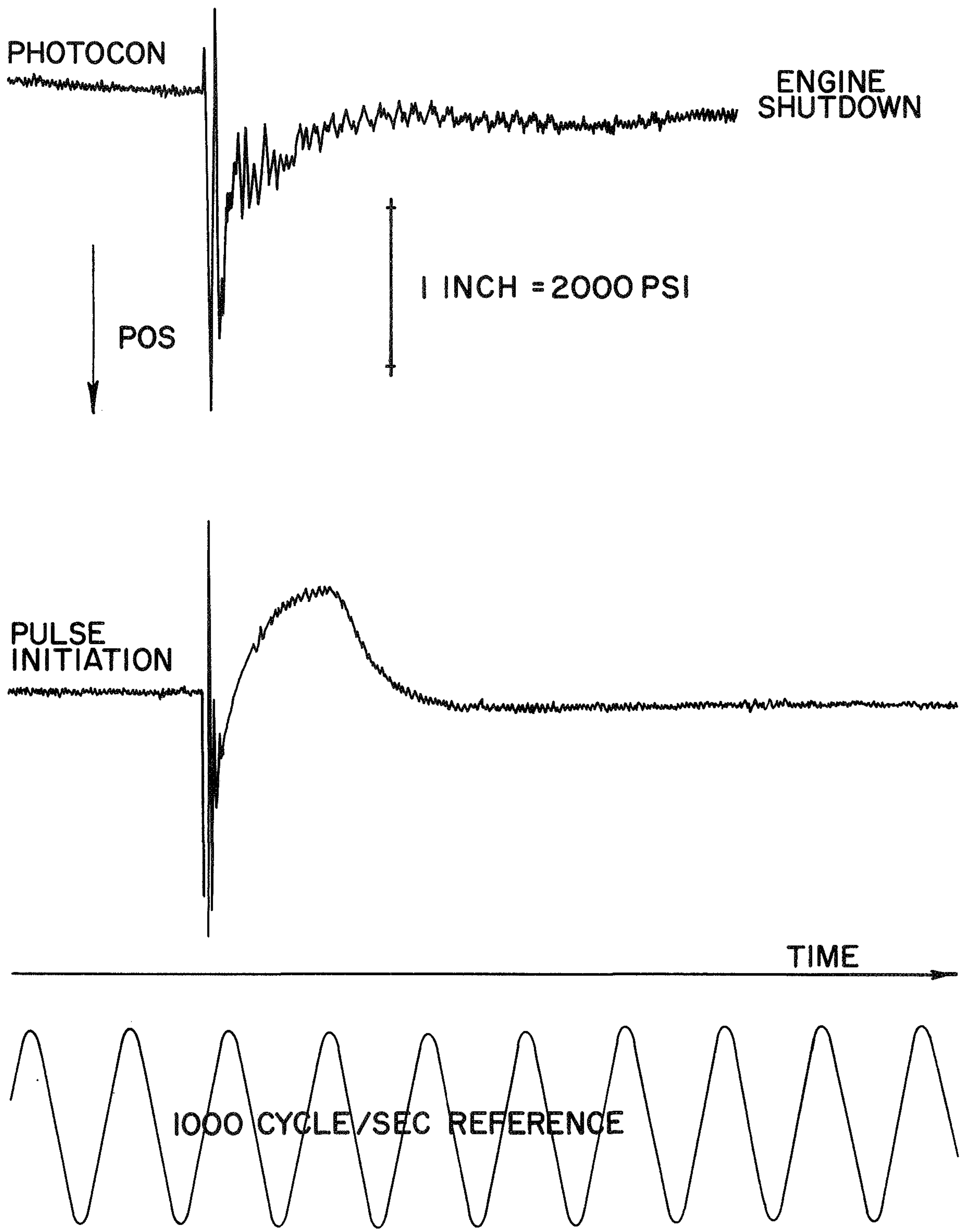


FIGURE 9 RUN 50 PHOTOCON PULSE TRACE

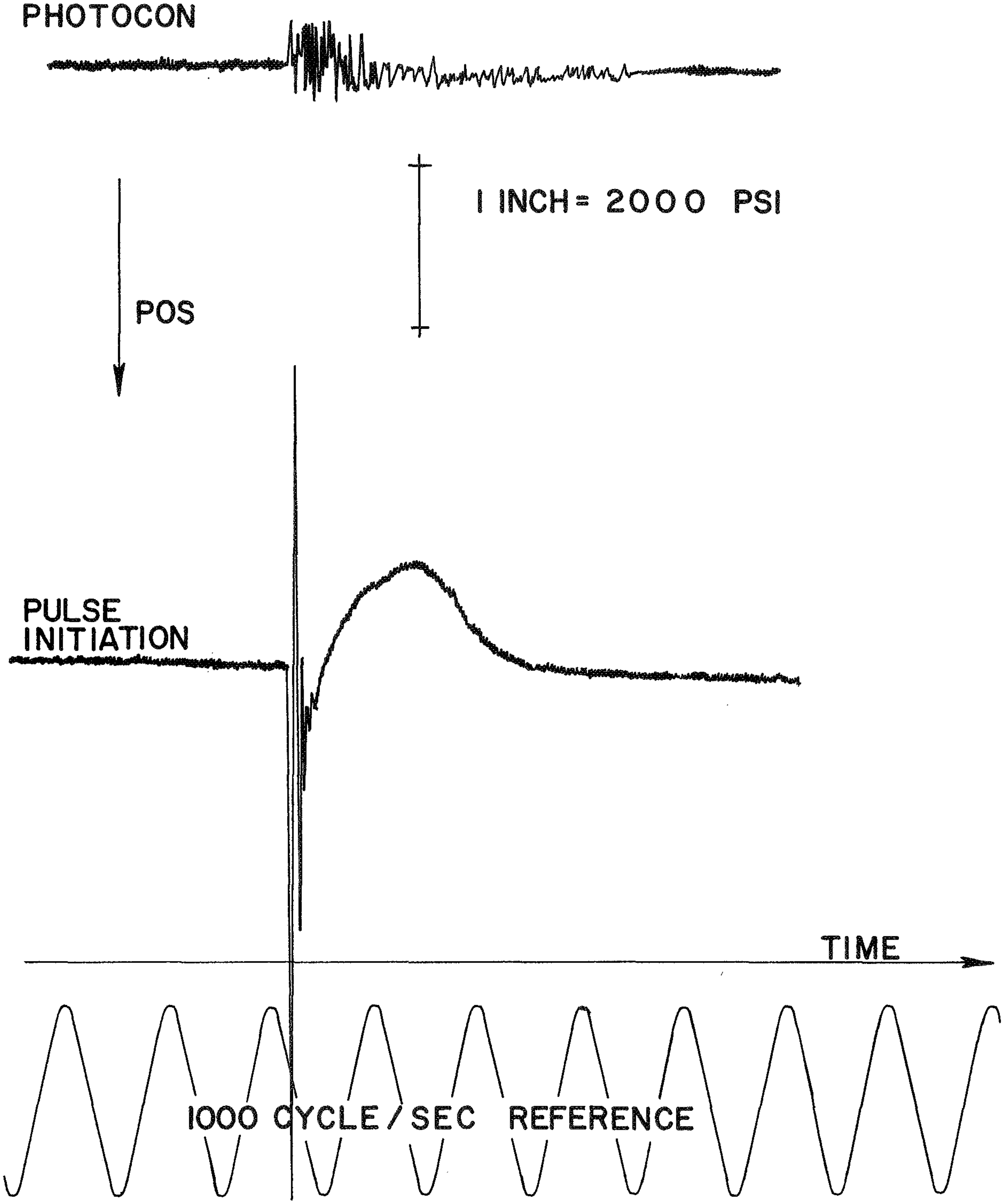


FIGURE 10 RUN 51 7400 TAPE PLAYBACK

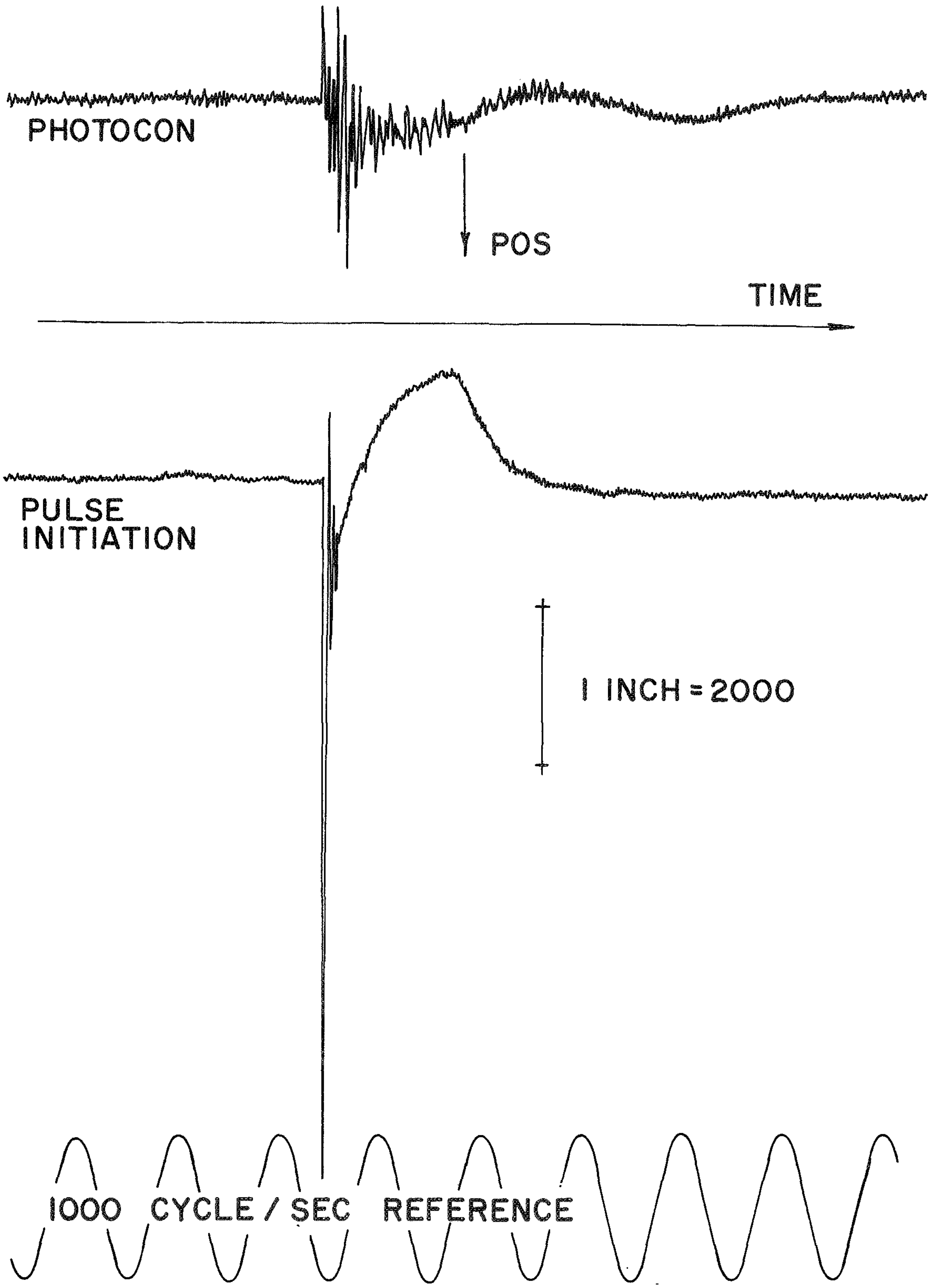


FIGURE II RUN 52 7400 TAPE PLAYBACK

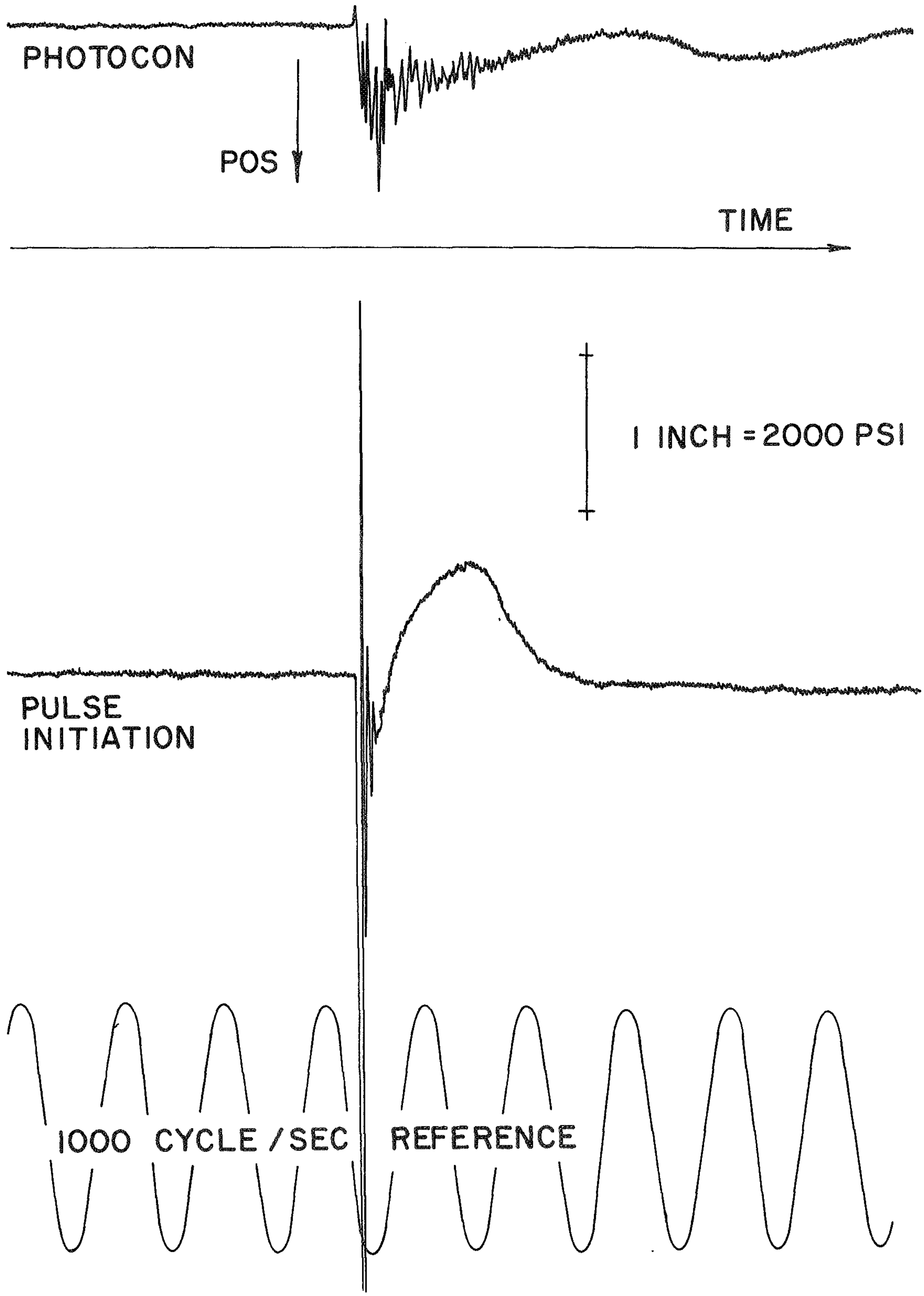
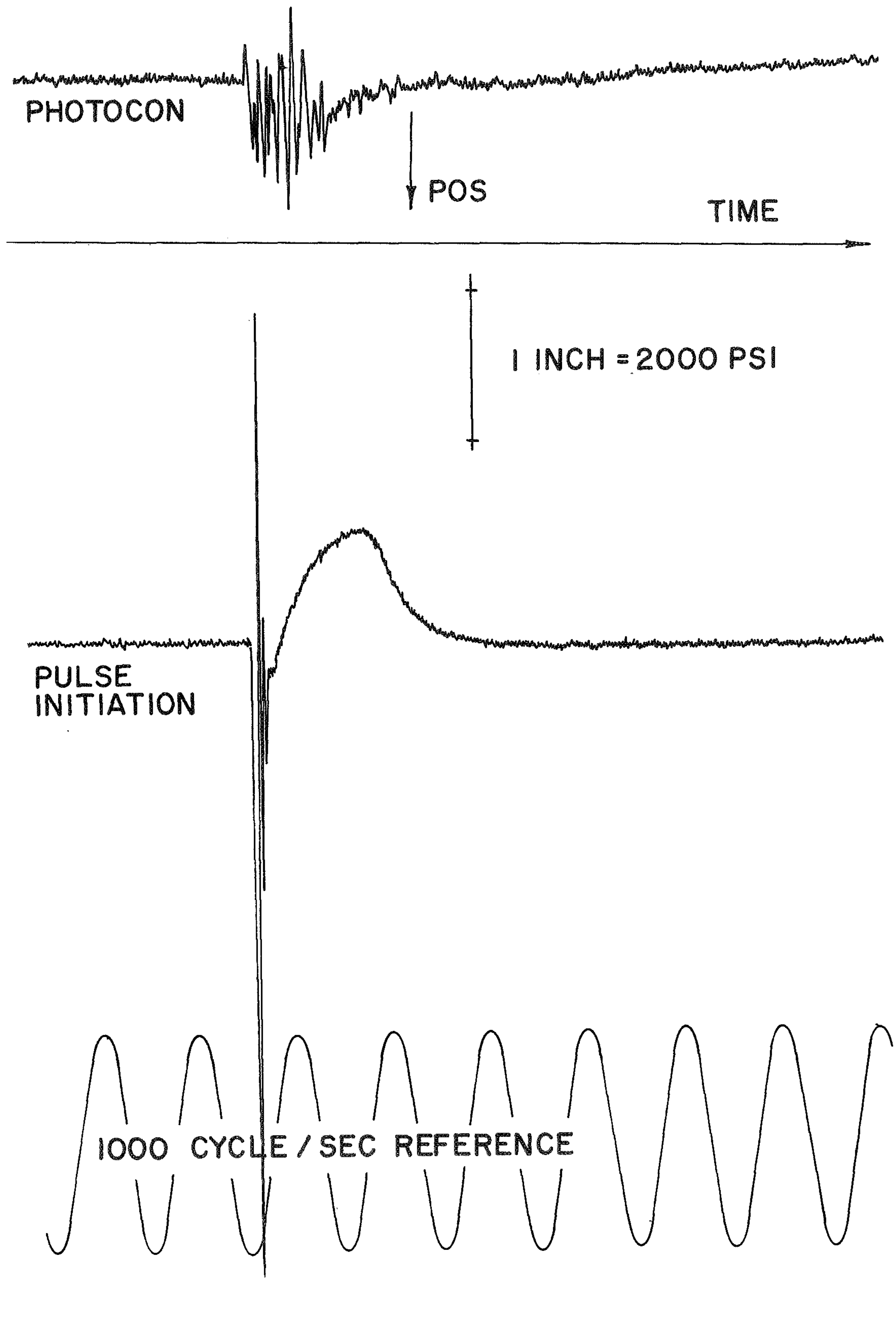


FIGURE 12 RUN 53 PLAYBACK FROM 7400 ANALOG TAPE



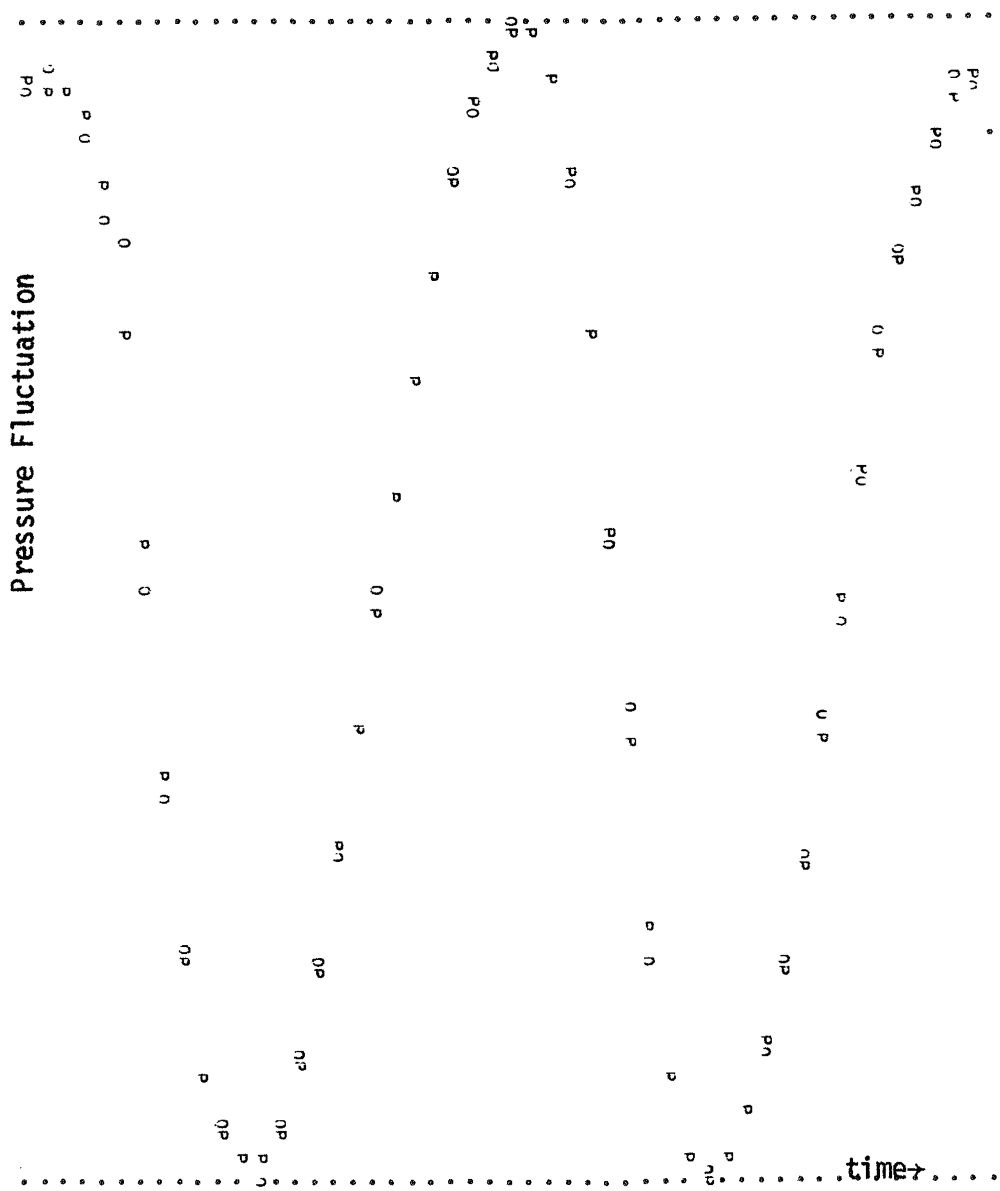


Figure 13. CURVE FIT OF HARMONIC PHOTOCON PRESSURE TRACE

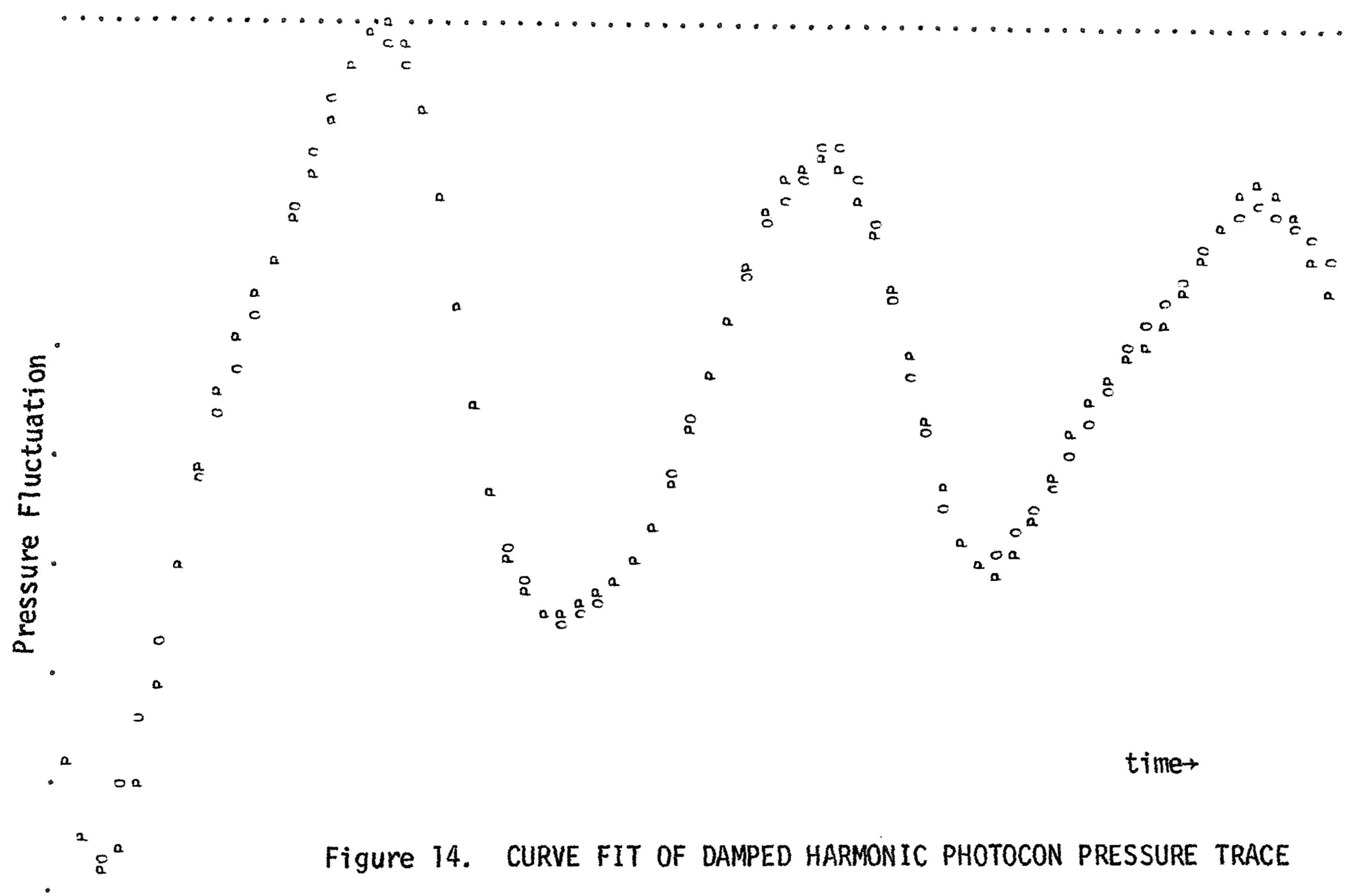


Figure 14. CURVE FIT OF DAMPED HARMONIC PHOTOCON PRESSURE TRACE

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